Science with the Space Interferometry Mission

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SIM Taking the Measure of the Universe

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The Space Interferometry Mission (SIM) will be NASA's first space-based optical interferometer designed for precision astrometry. SIM will produce a wealth of new astronomical data and serve as a technology pathfinder for future astrophysics missions. The SIM architecture uses a 10-m Michelson interferometer in Earth-trailing solar orbit to provide 4 microarcsecond (μas) precision absolute position measurements of stars down to 20 magnitude. The corresponding parallax accuracy allows distance measurements to 10% accuracy on the far side of the Galaxy. With high-precision proper motions derived during its 5-year lifetime, SIM will address a variety of science questions relating to the formation and dynamics of our Galaxy. SIM will also demonstrate interferometric nulling with suppression of the on-axis starlight to a level of 10^{-4}. In this paper we present selected topics from the SIM science program focusing on some specific astronomical questions to be addressed.

Introduction

The Space Interferometry Mission (SIM) is designed as a space-based 10-m baseline Michelson optical interferometer operating in the visible waveband. This mission will open up many areas of astrophysics, via astrometry with unprecedented accuracy. Over a narrow field of view SIM is expected to achieve an accuracy of 1μas. In this mode, SIM will search for planetary companions to nearby stars, by detecting the astrometric 'wobble' relative to a nearby (<1°) reference star. In its wide-angle mode, SIM will be capable to provide a 4 μas precision absolute position measurements of stars, with parallaxes to comparable accuracy, at the end of a 5-year mission. The expected proper motion accuracy is around 2μas/yr, corresponding to a transverse velocity of 10 m/s at a distance of 1 kpc.

The SIM instrument consists of three simultaneously operated Michelson Interferometers. While one interferometer determines the angle between its baseline and the science target, the other two interferometers determine the orientation of the baseline vector with respect to bright reference stars. The aperture diameter for each interferometer is 0.3 meters. The telescope field of regard is 15°; wide-angle astrometry is performed by measuring the change in white-light fringe delay, between targets. A summary of the key instrument and mission parameters is given in Table 1.

SIM will also operate as an imaging instrument, using aperture synthesis to provide a fully diffraction-limited aperture of 10 m in the optical band. The image resolution will be an unprecedented 10 milliarcsec in the optical. High dynamic range images will be possible because of the instrument stability and accurate fringe calibration. An example of an imaging target for SIM is a nearby active galactic nucleus with strong H-α line emission near its center. By imaging the line-emitting gas, SIM will measure the mass distribution in the very dense central region.

As well as opening up a number of fundamental areas of astronomy, via precision astrometry, SIM will serve as a technology pathfinder for future astrophysics missions, such as the Next Generation Space Telescope (NGST) and

Terrestrial Planet Finder (TPF). Many key technologies needed by future missions will be demonstrated by SIM, then carried over directly or readily adapted. Of particular relevance to TPF is the nulling beam combiner, which operates by applying a polarization flip to one arm of the interferometer. This is designed to yield a null depth (suppression of on-axis light) to 10^{-4}. A scientific goal of this observing mode is in studying the reflected light from dust disks around main-sequence stars. Nulling mode greatly increases the effective sensitivity to a disk, by canceling most of the light from the bright central star.

SIM is part of a NASA technology development plan which includes ground-based optical/IR interferometers, laboratory testbeds, flight verification of components, and space-based missions. The long-range goal of this program is to enhance the capability of future missions while reducing mission cost and risk. For more information on SIM, and the Interferometry Technology Program at JPL, visit our web site at: http://sim.jpl.nasa.gov

Table1:

Instrument and Mission Parameters	
Baseline	10 m
Wavelength Range	0.4 - 0.9 μm
Telescope Aperture	0.3m diameter
Astrometric Field of Regard	15°
Detector	Silicon CCD
Orbit	Earth-Trailing solar orbit
Launch Date	Mid-2005
Mission Duration	5 years
Astrometry (wide-angle)	4 μas accuracy
Astrometric Sensitivity	20 mag in 4 hours
Astrometry (narrow-angle)	1 μas accuracy
Interferometric Nulling	Null depth 10^{-4}

Astrometric Program Highlights

SIM offers the ability to make astrometric measurements with an accuracy far in excess of ground-based observations, or any other space mission in the near term. It therefore has tremendous potential for unexpected results, as well as contributing strongly to known problems in stellar astrophysics, planet detection, and galactic dynamics. With an absolute positional accuracy of 4 μas, SIM will improve on the best currently available measures (from the ESA Hipparcos mission) by more than two orders of magnitude. SIM will provide parallaxes accurate to 10% and transverse velocities accurate to 0.2 km/s anywhere in the Galaxy, to stars as faint as 20-th magnitude. With the addition of radial velocities from ground-based spectrometers, knowledge of all 6 position/velocity coordinates for objects of interest will allow astronomers to attack problems in stellar dynamics which are difficult without incomplete information.

The science program for SIM has been developed over a number of years by individuals and NASA advisory panels, most notably the SIM Science Working Group (SIMSWG). The SIMSWG has worked with the SIM Project to set requirements which define the design of the SIM interferometer, and its operation as a flight instrument. These parameters are set, not by any one individual scientific objective, but jointly by the set of objectives which constitute the science program. Some specific examples include:

- **Astrometric Detection of Earth-Mass Planets.** SIM will be able to detect the presence, and unambiguously measure the mass, of an earth-mass planet orbiting any of approx. the 100 nearest stars, via the gravitational perturbation it exerts on its parent star, though only a few such targets would be solar-type stars.

- **Detection of Brown Dwarfs and Massive Planets.** SIM will be able to detect sub-stellar companions (gas giant planets and brown dwarfs) around a large sample of nearby stars, and neutron stars and black holes around more distant stars, by measuring their astrometric perturbation on the primary star.

- **Stellar Dynamics of the Galaxy.** Using precision astrometry, SIM will address many fundamental questions concerning the mass distribution in our Galaxy, the dynamics of its stars, and the evolution of its stellar populations.

- **Masses and Evolution of Stars in Close Binary Systems.** By detecting the astrometric signature of the binary star orbit, SIM can determine the masses and orbits of a large number of ordinary binary star systems, as well as more exotic systems: white dwarf/CVs, neutron stars and black holes.

- **Stellar Luminosities and Calibration of Distance Indicators.** SIM will calibrate the luminosities of Cepheid and RR Lyrae 'standard candle' variable stars, and planetary nebulae. These sources are used as standard candles in distance determinations for calculating the Hubble constant, and in distance measurements to globular clusters.

- **Ages of Globular Clusters.** Stellar evolution models for clusters apparently conflict with the age of the universe inferred from the Hubble expansion. SIM will measure the distances to globular clusters directly using trigonometric parallax, and hence the luminosities of the oldest main-sequence stars can be determined. Subtle effects due to reddening and metallicity effects can be studied.

- **Dynamics of Small Stellar Systems.** By measuring the proper motions of globular clusters, the mass distribution of the Galaxy can be determined. This will help our understanding of the formation of the Galactic halo and the globular cluster system. Tidal tails from disrupted dwarf spheroidal galaxies also provide a powerful means of tracing the Galactic potential.

- **Rotational Parallaxes.** Distances to nearby spiral galaxies can be measured directly, without use of luminosity-based indicators, using proper motions of their brightest stars due to rotation of the disk about the center of the galaxy.

- **MACHO Gravitational Microlensing Events.** SIM will be able to detect the astrometric signature of microlensing events caused by massive compact halo objects (MACHOs) along the line of sight. Masses for these objects can be inferred, providing important clues to the nature of dark matter in the Galaxy.

In the following sections we present selected topics from the science program focusing on specific astronomical questions to be addressed. These highlights are not intended to be comprehensive, but indicate the breadth of the proposed SIM science program.

Planets around Nearby Stars

The discovery of planets around several nearby stars has brought into focus a long standing, but poorly understood problem in astronomy, namely the formation of planetary systems. These new data are the first solid pieces in a puzzle which will take some time to unravel. SIM will contribute strongly to the observational database available for testing of solar-system formation theories, by searching for planets. It will be capable of detecting planets down to Earth mass around the nearest stars, and Jupiter-mass planets out to a kiloparsec.

Thus an important goal for the mission is to detect the presence of earth-sized planets orbiting nearby solar-type stars and study their characteristics in order to learn about the formation and evolution of planetary systems that might include habitable planets. A secondary goal is to identify good targets for the Terrestrial Planet Finder, which will directly detect light from extra-solar planets. As mentioned above, SIM also serves as a technological precursor for TPF. To do this, SIM will search for earth-sized planets orbiting in or near the habitable zones of 50 of the most suitable solar-type stars.

Planets are extremely faint compared to the star around which they orbit—typically one billion times fainter in the visible waveband, and too faint for SIM to detect directly. Instead SIM detects the presence of a comparatively small body, such as a planet, around a star from the 'wobble' on its motion which can be detected by tracing the motion of the center of light of the system. There are two possible indirect techniques: the first utilizes the Doppler shift resulting from the radial motion of the star. With a resolution of the order of 10 meters per second, it has been possible to detect giant planets around several solar-type stars Mayor & Queloz (1995), Marcy & Butler (1996). With this technique, the mass of the planet is unknown to a factor *sin(i)* where *i* is the inclination of orbit plane to the line of sight. The second indirect technique monitors the reflex motion of the target star around the common center of mass, with respect to a local frame of distant objects.

In our own solar system, the astromertric signature is dominated by Jupiter and Saturn. Seen from a distance of 10 pc, the peak-to-peak wobble would be about 1300 μas, in a characteristic spiral pattern.

The recently-discovered triple planet system Upsilon Andromedae (Butler et al. 1999) would produce an astrometric signature qualitatively very similar to our own solar system. Astrometric and radial-velocity

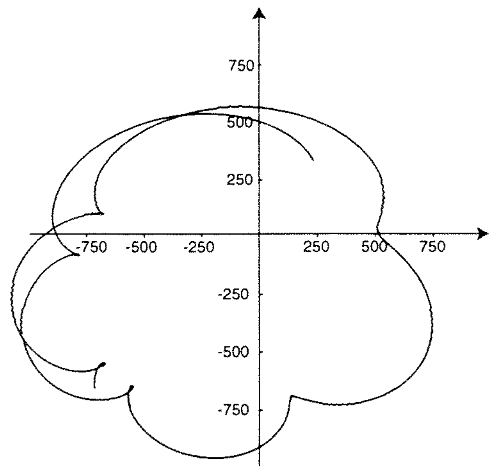

Figure1: A possible astrometric signature (axes in microarcseconds) for the Upsilon Andromedae multi-planetary system. System is assumed to be co-planar with an orbital inclinations of 40 degrees, followed over 5 years.

methods are complementatary. Radial-velocity methods are more sensitive to very tightly bound short-period planets, while SIM is much more sensitive to lower-mass planets further out.

SIM has a unique role to play in the understanding of multiple systems, especially since it is likely that such systems are common. SIM it can determine the position angle and inclination of each orbit (thereby measuring the planet masses), and even more importantly, test the assumption that the orbits are co-planar. And since SIM is a targeted instrument, it can make sufficient measurements to fully sample the expected signatures.

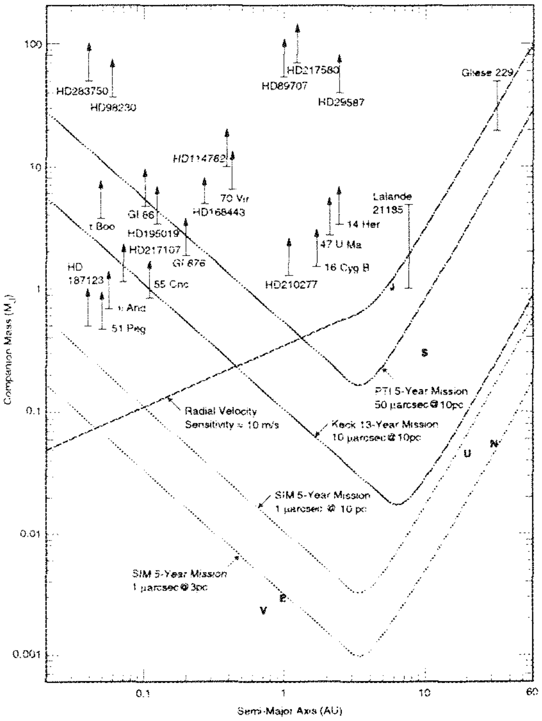

Figure 2: Planet searching by detecting reflex motion of the target star (solar-type at 10pc distance), showing the capabilities of ground based radial velocity measurements, the Keck Interferometer, and SIM.

SIM performs this second technique via narrow-angle astrometry. The science interferometer alternately observes the candidate star and distant background stars within about one degree on the sky. By carefully selecting those reference stars forming the local frame, repeated observations will lead to a very high relative positional accuracy of the science target with respect to this local frame. In its narrow-angle regime, SIM will reach a precision of about 0.25μas during the mission lifetime. This corresponds to a detection of to the reflex motion induced by an Earth-mass planets around the nearest few G-type stars. The two-dimensional astrometric information obtained then uniquely defines the orbital inclination of the companion, and hence a unique mass (since the distance is known accurately via parallax).

SIM will be able to detect large terrestrial planets orbiting nearby solar-type stars and study their characteristics in order to learn about the role of rocky cores in the formation and evolution of planetary systems. To do this it will search 200 main-sequence stars for large terrestrial planets which formed as rocky cores in the region closer to their parent stars than the inner boundary of the ice condensation zones in their proto-planetary disks. Where feasible, orbital solutions and planet masses will be derived. Once one planet is detected, the search will be extended for for evidence of additional planets in those systems.

For this program, terrestrial planets (5 to 10 earth masses) may be defined as having the following characteristics i) they should be inside the inner boundary of the ice condensation zones: periods of 1 to 10 years depending on the spectral type of the star; ii) their parent star should be a main-sequence stars: types A through M (O and B are too rare and therefore too distant). The targets should be known not to have companions which would interfere with the formation or survival of large terrestrial planets. Figure 2 shows where the known planets (including our own solar system) lie in the mass - orbit-radius plane, together with the sensitivity limits of the two main detection methods.

Orbits of Small Stellar Systems

Globular clusters are one of the few classes of object that can be seen - and whose distances can be accurately determined - throughout the Galaxy. The spatial distribution and kinematics of the globular cluster system provide a powerful probe of the mass distribution of the Galaxy, the phase-space and metallicity distribution of the cluster system, the formation of the Galactic halo, and the evolution of the cluster system itself. Many authors have analyzed the globular cluster system with these aims in mind (see Thomas 1989 and references therein). All of these analyses have used angular positions, distances and radial velocities---4 of the 6 phase-space coordinates. With this information it is possible to show that the phase-space distribution is approximately isotropic (i.e. uniform on the energy hyper-surface) within the solar circle. However, it is not possible to constrain strongly either the phase-space distribution outside the solar circle (in particular whether the orbits are isotropic or predominantly radial) or the Galactic potential (in particular whether the Galaxy has a massive dark halo).

Accurate proper motions can greatly enhance the power of such analyses by providing the final two of the six phase-space coordinates. Ground-based proper motions are now available for ~25 of the ~200 Galactic globular clusters (see Dauphole et al. 1996), about half of which have claimed errors < 1 mas/yr (corresponding to 50 km/s at 10 kpc). Neither the number nor the accuracy of these measurements is sufficient to constrain strongly the kinematics of the cluster system.

The satellite stellar systems at >20 kpc from the Galactic center (dwarf galaxies and distant globular clusters) constrain the mass and extent of the Galactic dark halo and offer insights into the formation of the Galaxy by gravitational collapse. These systems are less useful if only radial velocities are available, as there is a degeneracy between the effects of a massive halo and a predominantly radial velocity distribution, both of which lead to large rms radial velocities. This degeneracy can be removed by proper motion measurements. Determining the proper motions of all of the satellites of the Galaxy to an accuracy of 5 km/s will be part of the Science Requirements for SIM (Unwin et al.(1998)).

Of ~150 known globular clusters, over 90% are within 30 kpc of the Sun (see Harris (1996)). Measuring the transverse velocity of these clusters to a level of 5 km/s requires a proper motion accuracy of 35μas/yr, a relatively large signal for SIM. The number of stars required per cluster depends on the richness of the cluster compared to the background but probably an average of 5-10 stars is desirable to eliminate possible background stars or occasional stars with anomalous velocities. Almost all of the clusters have an adequate supply of red giant stars with V<18. The exceptions are a handful of heavily reddened clusters near the Galactic center, and a few very distant clusters. The reddened clusters can be discarded from the sample without significant loss of information. Note that distant clusters are important for probing the mass and phase-space distribution at radii >20 kpc, as discussed below.

There are 25 satellites of the Galaxy with Galactocentric radii between 20 and 250 kpc and known radial velocities (16 globular clusters, 8 dwarf spheroidal galaxies, and the Magellanic Clouds). Most of these are at distances <140 kpc, except for the dwarf spheroidals Leo I and Leo II at 220 kpc. Determining the tangential velocity of Leo I and II to 5 km/s requires a proper motion accuracy of 5 μas/yr. All of the inner dwarf spheroidals have stars at V<18-18.5, but the Leo galaxies and the distant globular clusters require reaching V=19.5-20. The brightest stars in the Sagittarius galaxy have V ~15-16 and should be easy targets for SIM.

Dynamics and Evolution of Binary Stars

Binary star systems which contain at least one compact object provide extraordinary laboratories for exploring physical conditions unobtainable on Earth. Studies of the current binary parameters of such systems have provided the strongest evidence yet obtained for the existence of black holes and of gravitational wave radiation. The evolution of these systems is complex, due to the effects of mass transfer and mass loss. The origin of Type I supernovae, millisecond pulsars, low mass X-ray binaries, and globular cluster X-ray sources all involve unsolved issues in the evolution of compact binary systems. The combination of excellent spatial resolution and high sensitivity will enable SIM to determine the orbital parameters of these systems to unprecedented accuracy. The current dearth of definitive mass and orbit determinations suggests that even a modest number of SIM measurements will represent a breakthrough in this field. Specifically, SIM will be able to obtain precise masses for stellar constituents in spectroscopic binaries in order to refine the mass-luminosity relation for sub-solar mass stars in the Galactic disk and, for the first time, to determine directly the mass-luminosity relation for metal-poor stars in the Galactic halo.

Fine structure in the mass-luminosity relation corresponds to changes in the physics of stellar interiors. Hence the mass-luminosity relation is fundamental to our understanding of both the mass distribution in the Galaxy and of stellar structure, particularly in determining the exact location of the hydrogen-burning limit. At present, the relation for solar-metallicity stars less massive than 0.5 M_{Sun} is defined by only 20 stars. All are astrometric binaries, and the masses are determined to a typical precision of 20 to 40%. Mass determinations for metal-poor stars are effectively non-existent. SIM can determine high-accuracy parallaxes and photocentric orbits for known, nearby, late-type spectroscopic binaries in both the general field and in clusters, achieving mass estimates with a precision of better than 2%.

Double lined spectroscopic binaries are perhaps the most interesting targets because the combination of measuring both the parallax and the photocentric orbit provides a complete description of the system. The parallax provides the absolute magnitude of the combined light. The shape of the photocentric orbit gives the inclination which, combined with a_1 *sin(i)* and a_2 *sin(i)* from the spectroscopic measurements, allows direct determination of the individual masses. The flux ratio of the two components can be derived in several ways: directly using interferometer visibility measurements, if the system is resolved; from the relative line-strengths in the spectra; or from the ratio between the projected absolute semi-major axis and the photocentric semi-major axis at a given wavelength.

Table 2: Late Type Galaxies Appropriate for Rotational Parallax Determination

NGC		Type	i	d	W(20)	μ(M)	μ(m)	V(M_V=-8.5)
			deg	Mpc	Km/s	μas/yr	μas/yr	mag
55		Sc	84	2.0	196	1	10	18.0
224	M31	Sb	77	0.77*	533	16	75	16.0
247		Sc	76	2.2	220	3	11	18.2
253		Sc	81	3.0	434	3	16	18.9
300		Sc	44	2.2*	163	8	11	18.2
598	M33	Sc	56	0.84*	192	16	29	16.1
3031	M81	Sb	57	3.6*	455	10	18	19.3
7793		Sd	47	4.1	193	5	7	19.6

* Distance from Freedman and collaborators

Uncertainty in the mass-luminosity relation is dominated by errors in mass rather than luminosity, since $L \sim M^{3.5}$. The goal is to determine masses accurate to better than 1% for stars with $1.0 > \{M/M_{Sun}\} > 0.08$, corresponding to $20 > M_V > 4$ or $11 > M_K > 3$. This demands uncertainties of no more than 0.3% in *sin(i)*, since the derived mass varies with the cube of the de-projected semi-major axis. Note that even for the nearby Hyades cluster the individual parallaxes from Hipparcos are good to only slightly better than 5%. Sampling the full mass range of field stars, and characterizing metallicity dependencies, requires a sample of at least 180 spectroscopic binaries distributed among the following categories: (a) 100 disk dwarfs drawn from the general field; (b) 30 binaries from the Hyades, Pleiades, Praesepe and other open clusters; (c) 30 halo F, G, and K field subdwarfs.

Dynamics of the Local Universe

Dynamical studies of the Local Group of galaxies provide our most detailed probe of the mass distribution and the development of structure in a typical collapsing group on 1 Mpc scales. Investigations of Local Group kinematics using radial velocities and distances have been conducted in the past by a number of researchers (see Peebles (1996) and references therein). SIM will enhance the power of these studies not only by providing more accurate distances but more importantly by providing proper motions for a number of galaxies in the Local Group. Each such measurement means that all six phase-space coordinates of the galaxy will be known and these measurements combined with the age of the Universe and constraints from linear perturbation theory strongly over-determine the orbit for a given mass distribution. Apart from nearby satellites of our own Galaxy, the most promising candidates include M31, M33, NGC 6822, IC 1613, WLM, and IC 10.

There are over 200 known galaxies outside the Local Group but within 5 Mpc. If, as most cosmologists assume, the peculiar velocities of these galaxies relative to the Hubble flow arise from gravitational instability, they reflect the initial perturbation spectrum and the distribution of mass in the universe. Proper motions are much more powerful probes of structure development than radial velocities because they are orthogonal to the Hubble expansion. A typical peculiar velocity of 100 km/s corresponds to 4 μas/yr at 5 Mpc.

Many of the nearby galaxies are clustered into groups (the main groups within 5 Mpc include IC 342, M81, NGC 4244, Cen A, Sculptor, and perhaps M101). The dynamics of virialized groups can be used to probe the distribution of dark matter; the principal limitation to analyses of this kind is that redshift provides only one of the three velocity components of each galaxy. By measuring proper motions, SIM can determine the other two velocity components and thereby dramatically enhance our understanding of the orbits and masses in nearby groups.

The brightest stars in late-type galaxies at 1 Mpc have $V < 18$ and hence are easily measurable with SIM. A typical transverse velocity of 100 km/s corresponds to 20 μas/yr at 1 Mpc. Such measurements do not significantly challenge the requirements for SIM. However, the elliptical satellite galaxies of M31 (NGC 205, M32, and several dwarf spheroidals) cannot be measured by SIM since their brightest stars are too faint, although the central nucleus of M32 might be bright enough.

In giant galaxies with recent star formation the brightest stars at visual magnitudes are late A or F-type supergiants with $M_V \sim -9$. An accuracy of ±20 km/s requires a proper motion accuracy of 1 μas/yr. The SIM limiting sensitivity of $V = 20$ leads to 5 Mpc as the maximum distance for this method.

Rotational Parallaxes of Nearby Spiral Galaxies

SIM will yield precise distance measurements for the nearest spiral galaxies with uncertainties at the few percent level through the technique of rotational parallaxes. Precise knowledge of the distances of nearby galaxies is important for calibrating the cosmic distance scale, understanding the kinematics and dynamics of the local group, and comparing stellar populations in different galaxies.

This technique rests on the near circular motions seen in the disks of intermediate to late type spiral galaxies (see Peterson 1995). The measurement of proper motions of individual stars at several locations in the disk of a spiral galaxy, when combined with ground-based radial velocity measurements, can provide an independent measurement of the rotation curve at the location, the inclination of the disk and the distance. Some averaging is required to average out peculiar motions of the individual stars, and systematic perturbations to the motions due to warping of the disks and the presence of spiral arm structure. These will probably be the limiting systematic effects, but should not interfere with distance determinations to worse than 5% in the more massive systems.

Because SIM will directly measure the distance to nearby spiral galaxies, it eliminates potential major uncertainties due to luminosity-based distance indicators. It will provide a direct calibration of the Tully-Fisher (1988) relation used to measure larger distances in the universe. Luminosity calibrations of bright Population I objects in a variety of external systems will then be available, including the full range of Cepheids and RR Lyrae stars observable in nearby spiral systems. For the nearest spiral galaxies, the desired signal is relatively large for SIM. For example, in the Andromeda galaxy (M31), a transverse velocity of 200 km/s yields a proper motion of about 70 μas/yr. Combining the proper motions with a deprojected velocity map of the galaxy obtained from 21-cm neutral hydrogen mapping then introduces a length scale, which determines the distance to Andromeda.

The goal is to obtain rotational parallaxes to every large spiral galaxy with individual Population I stars bright enough to be within the observing limit of SIM. The ideal galaxy is one viewed at an inclination of 45° (so that there is a significance in both the proper motions modulations and the radial velocities). Nearly edge-on systems can also be used but the inclinations, which enter weakly, will have to be estimated by other means. Face on systems will be limited by the accuracy of the radial velocities. All but M31 and possibly M33 can be observed by SIM in narrow-angle mode (since it is *differences* in proper motions across the systems that are critical). With an assumed magnitude limit of V=20, the galaxies in Table 2 should be observed to achieve the science goal.

SIM will measure the distances of each of these galaxies to the limits set by systematic errors in radial velocity measurements, assumed to be 10 km/s, or in the proper motions. For the closer systems, this is easily accomplished, so for M31 and M33 the process could be made to be wholly self-consistent, thereby avoiding as many systematic errors as possible. To do this, SIM will need to determine the velocity curve through the range of radial distances as well as solve for the other parameters. Thus, for these two nearby systems we expect to observe 25 bright members in each quadrant over the range of distances where the rotation curve is nominally constant. For the other galaxies, 25 objects total, given guidance from existing rotation curves, should suffice to identify "run away" and other anomalous objects and achieve solutions accurate to 5% in distance (10% in magnitude).

Astrometric Gravitational Microlensing Events

Gravitational microlensing events may be used to indirectly study the population of massive compact objects in the Galaxy that may be a significant component of the dark matter inferred from dynamical considerations. A significant number of such events have been detected photometrically from ground-based surveys, though the results have raised a number of new questions. A difficulty in interpreting the MACHO collaboration results is that the events are observed photometrically, which does not uniquely determine the mass of the lens—instead results much be interpreted in the context of a halo model (Alcock 1996).

SIM can also detect microlensing events, not via photometry, but by detecting the astrometric signatures created in a microlensing encounter. Physical properties of the source and lens may be inferred directly from the encounter data. Boden et al. (1998) demonstrate the application of simulated microarcsecond astrometry to reconstruct the mass and kinematic properties of the lens—something not currently possible with the vast majority of photometric-only detections. Additionally, Paczynski (1998) describes applications of the technique to measure the masses of individual stars, and the measurement of stellar diameters. Of the three of these projects, the study of halo lenses is probably the most significant.

Because the positions and intensities of gravitational lens images evolve non-trivially in time during a microlensing encounter, microlensing (where by definition the lensing images are unresolved by the observer) produces both photometric and astrometric observables. Monitoring these observables over time yields an observable set that can be used to estimate lens and source parameters. While some parameters are amenable to narrow-angle techniques, SIM's wide-angle accuracy is sufficient to determine mass and distance for the vast majority of Galactic bulge and LMC/SMC events.

SIM cannot detect microlensing events a priori—instead it must rely on other mechanisms for event detection. The most straightforward strategy would be to key on events detected photometrically in wide-field surveys such as the MACHO and OGLE2 projects (or their successors). In this case, the best strategy would be a combined reduction of both the photometric and astrometric data (see similar comments in Hog et al. (1995) - examples and expected performance are outlined in Boden, Shao & Van Buren (1998)). SIM would observe in a 'target-of-opportunity' mode, responding in a few days, catching the event near photometric maximum where the astrometric motions are the most dynamic. Post photometric maximum this astrometry must span a roughly 3-year period to allow sufficient sampling of both the lensing event itself and the motions of the background source.

The science requirement for SIM will be to determine mass, distance, and kinematics for a minimum of 5 LMC/SMC events and 10 Galactic bulge events to $<$ 15% accuracy in mass. Based on simulation results described by Boden, this requires periodic astrometry (approx. every 2 days near maximum amplification) at the ~10μas level for V ~19 LMC/SMC sources, and ~15μas on V ~16 Galactic bulge sources. It also presumes that the events are photometrically detected and monitored during the photometric amplification.

Conclusions

The Space Interferometry Mission will make many important contributions to astronomy and astrophysics during its 5-year mission. Many of its science objectives are related to the goals of NASA Origins theme, including wealth of data concerning the pervasiveness of planetary systems (and sub-stellar companions) around nearby stars, and mass statistics of these systems.

SIM will provide key data for a variety of questions in astrophysics, including:

- Searching for other solar systems, and studying the process of star and solar system formation
- Studying the mass distribution and evolutionary history of the Galaxy, using globular clusters and dwarf spheroidal galaxies as probes
- Calibrating distance and age indicators used for measuring the cosmic distance scale
- Directly measuring distances to spiral galaxies, independent of all luminosity-based distance indicators
- Characterizing dark matter in the Galaxy by observing microlensing events

Acknowledgement

The SIM science program, some of which is highlighted in this paper, represents the efforts of many astronomers who have addressed the potential of microarcsecond astrometry, and we thank them very much for their efforts. In particular the SIM Science Working Group (co-chaired by Deane Peterson and Mike Shao) has played a key role in defining design requirements for SIM, and some of their material is reproduced herein with their permission. We would also like to thank many colleagues for lively discussions, especially Andrew Boden, Jo Pitesky, Dave Van Buren and Jeffrey Yu. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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